Title	Precise Measurement of dp Elastic Scattering at 270 MeV and Three-Nucleon Force Effects
Author(s)	Sakai, H; Sekiguchi, K; Witala, H; Glockle, W; Hatano, M; Kamada, Hiroyuki; Kato, H; Maeda, Y; Nogga, A; Ohnishi, T; Okamura, H; Sakamoto, N; Sakoda, S; Satou, Y; Suda, K; Tamii, A; Uesaka, T; Wakasa, T; Yako, K
Issue Date	2000-06
URL	http://hdl.handle.net/10228/766
Rights	Copyright ©2000 The American Physical Society

Precise Measurement of dp Elastic Scattering at 270 MeV and Three-Nucleon Force Effects

H. Sakai,[1,5,*] K. Sekiguchi,[1] H. Witała,[2] W. Glöckle,[3] M. Hatano,[1] H. Kamada,[3] H. Kato,[1] Y. Maeda,[1] A. Nogga,[3] T. Ohnishi,[1] H. Okamura,[4] N. Sakamoto,[5] S. Sakoda,[1] Y. Satou,[5] K. Suda,[4] A. Tamii,[1] T. Uesaka,[4] T. Wakasa,[6] and K. Yako[1]

[1]Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[2]Institute of Physics, Jagellonian University, PL-30059 Cracow, Poland
[3]Institut für Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[4]Department of Physics, Saitama University, Urawa, Saitama 338-8570, Japan
[5]The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan
[6]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
(Received 22 February 2000)

The cross section, the deuteron vector A_y^d and tensor analyzing powers A_{ij}, the polarization transfer coefficients $K_{ij}^{y'}$, and the induced polarization $P^{y'}$ were measured for the dp elastic scattering at 270 MeV. The cross section and A_y^d are well reproduced by Faddeev calculations with modern data-equivalent nucleon-nucleon forces plus the Tucson-Melbourne three-nucleon force. In contrast, A_{ij}, $K_{ij}^{y'}$, or $P^{y'}$ are not described by such calculations. These facts indicate the deficiencies in the spin dependence of the Tucson-Melbourne force and call for extended three-nucleon force models.

PACS numbers: 21.30.–x, 24.10.–i, 24.70.+s, 25.10.+s

Three-body forces, such as that between a satellite, the moon, and the Earth caused by tidal forces or the long range Axilrod-Teller force [1] between three atoms caused by mutual polarization of the electron clouds, are pervasive in nature. Also three-nucleon forces (3NF) have become more and more the topic of focus of both theoretical and experimental investigations. Although their existence is not doubted, what is looked for is a lucid signal in experimental data that can be tested by the present day 3NF models. Present day nucleon-nucleon (NN) forces are not capable to provide correct binding energies of light nuclei [2]. They are underbound and 3NFs are natural candidates to fill the gaps. The 3NFs arise naturally in the standard meson exchange picture [3,4] as well as in the more recent concept of chiral perturbation theory [5–7]. Their precise strength and detailed properties (spin and isopin dependencies) are still under debate [6,8,9]. The need for additional dynamics beyond NN forces only is also clearly seen in 3N scattering [10] and in the first theoretical results in 4N scattering [11]. One outstanding example is the low energy nucleon analyzing power A_y^N in elastic Nd scattering [10,12], which exhibits a strong discrepancy to NN force predictions only. An often used first model of a 3NF is the 2π exchange in the form called the Tucson-Melbourne parametrization (TM-3NF) [4]. Another version is the Urbana 3NF [13]. Both forces are well suited to shift the theoretical binding energies of three- and four-nucleon systems into the right places, but they should be probed in more detail in 3N scattering, where a great variety of scattering observables is available [10]. Both types of 3NFs just mentioned do not remove the discrepancy in A_y^N [14]. It is presently considered that this is caused by either defects in modern NN forces [15] or by still undiscovered 3NF properties such as spin-orbit interactions [5,6,8]. More insight both theoretically and experimentally is needed. This Letter is a step in that direction.

The 3N scattering observables are accessible theoretically, since recently it became possible to solve the dynamical 3N equations rigorously [10,16] using modern NN and 3N forces. They are also accessible experimentally, since new facilities became available for elaborate measurements of polarization degrees of freedom [17]. Naively one can expect that an analyzing power A_y is dominated by a spin-orbit interaction ($\ell \cdot s$), while tensor analyzing powers A_{ij} depend on tensor interactions (like through the deuteron D state) as well as on a $(\ell \cdot s)^2$ interaction. On the other hand, the polarization transfer coefficients should also be sensitive to a spin-spin interaction. Thus one should have a chance to study various aspects of 3NF effects in elastic Nd scattering.

Resently Witała *et al.* [18] pointed out that a signature of a 3NF might show up in the minimum region of the Nd elastic cross section at intermediate energies. The calculations with NN forces alone underestimate significantly the experimental data. This discrepancy is well accounted for by adding a 3NF [18]. The main part of the discrepancy is also explained by including the Δ isobar degrees of freedom explicitly [19] which is an important ingredient of a 3NF. As to the polarization observables the measurements are scarce at intermediate energies. Very recently the proton analyzing powers A_y^p for the $\vec{p}d$ scattering have been measured [20,21]. It is found that the observed A_y^p agrees with neither Faddeev calculations with or without a 3NF.

Sakamoto *et al.* [17] have measured the $\vec{d}p$ scattering cross sections and vector and tensor analyzing powers at $E_d = 270$ MeV. Data are compared with Faddeev calculations employing the old AV14 NN force [22] without

 0031-9007/00/84(23)/5288(4)$15.00

a 3NF. Again the observed cross section is found to be underestimated by 30% in the region of the cross section minimum. Also the analyzing powers are reproduced only moderately.

In order to assess further the 3NF effects, high quality data are needed to distinguish possible subtle 3NF effects and at the same time it is important to extend the measurement to new observables which are possibly sensitive to particular parts of a 3NF. In this Letter we present precise data on the dp cross section and the complete set of analyzing powers A_y^d, A_{xx}, A_{yy}, and A_{xz} at $E_d = 270$ MeV spanning nearly the whole angular range $\theta_{\mathrm{c.m.}} = 10°-180°$. Our former work [17] was only for $\theta_{\mathrm{c.m.}} = 57°-138°$. In addition, we present for the first time the polarization transfer measurement for the $\vec{d} + p \rightarrow \vec{p} + d$ elastic scattering. This measurement also yields an induced polarization $P^{y'}$ of the outgoing proton. Those results are compared with fully converged Faddeev calculations based on various modern NN forces together with the TM-3NF.

The experiment was performed at the RIKEN Accelerator Research Facility (RARF) using vector and tensor polarized deuteron beams of 270 MeV [23]. The polarization axis was rotated prior to the acceleration with a Wien filter system to the direction required for the measurement. The beam polarization was monitored by using dp scattering [17] and it was 60%–80% of the ideal value throughout the experiment. The CH_2 target with a thickness of 46.7 mg/cm^2 was bombarded, and either the scattered proton or deuteron was momentum analyzed by the magnetic spectrometer SMART [24].

The focal-plane polarimeter DPOL [25] was used to measure the proton polarization. It was primarily designed and optimized for deuteron polarization measurements. Therefore the effective analyzing power $\langle A_y \rangle$ of DPOL had to be calibrated for protons. It was done at 198 MeV by utilizing the induced polarization $P^{y'}$ of the $^{12}C(p, \vec{p})\,^{12}C$ elastic scattering. The vector analyzing power A_y for the time-reversed $^{12}C(\vec{p}, p)^{12}C$ elastic scattering at $E_p = 200$ MeV, hence $A_y = P^{y'}$, has been accurately measured at IUCF [26]. The calibration was performed at two different angles $\theta_{\mathrm{c.m.}} = 16°$ and $28°$ where the polarizations of 0.93 and -0.33 are expected [26], respectively. The graphite target with a thickness of 284 mg/cm^2 in the SMART scattering chamber was bombarded by an unpolarized proton beam of 200 MeV. The scattered protons bombarded the polarization analyzer target of DPOL which consisted of a graphite plate and a plastic scintillator with thicknesses of 5 cm and 13 mm, respectively. The left-right asymmetry of these double scattered protons was used to extract the $\langle A_y \rangle$ value as 0.48 ± 0.01 at $E_p = 198$ MeV. The energy dependence of $\langle A_y \rangle$ of DPOL has been estimated by a Monte Carlo simulation.

The measured cross section and analyzing powers (open circle) are shown in Fig. 1 together with the theoretical predictions and previous data (open square) from Sakamoto *et al.* [17]. Where the data overlap, good agreement is found between the present data and those of Ref. [17].

The statistical error for the cross section is better than $\pm 1.3\%$ over all the measured angles. The uncertainties of the target thickness and the charge collection of the beam were estimated by comparing the measured cross sections for the $p + p$ scattering with the calculated values by SAID [27]. This measurement was successively performed by

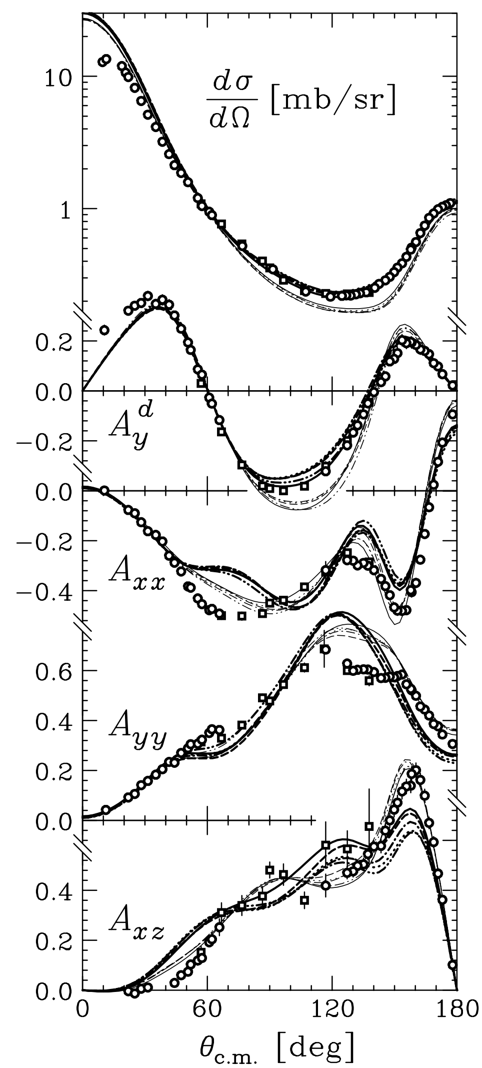

FIG. 1. Angular distributions of cross section and analyzing powers A_y^d, A_{xx}, A_{yy}, and A_{xz} for dp elastic scattering at 270 MeV. Experimental data (open circles and open squares from Ref. [17]) are compared with Faddeev calculations. Only statistical errors are indicated. Thin lines are based on NN forces alone using the CD-Bonn (solid), AV18 (dashed), Nijmegen-I (dotted), Nijmegen-II (dot-dashed), and Nijmegen-93 (dot-dot-dashed). Thick lines include the TM-3NF. The reduced χ^2 values for $\theta_{\mathrm{c.m.}} = 50°-180°$ with (without) 3NF for CD-Bonn are 16.9(225.2), 2.52(7.71), 31.6(29.8), 12.2(6.03), and 4.93(0.96) for $d\sigma/d\Omega$, A_y^d, A_{xx}, A_{yy}, and A_{xz}, respectively. Other NN forces give similar values.

changing the beam from deuteron to H_2^+ keeping all experimental conditions intact except for the magnetic field strength of SMART. The ratio of the observed cross section to the calculated one is 1.010 ± 0.013. Thus the systematic error is estimated to be smaller than 2%. In this way the high precision of the cross section has been achieved.

The analysis for nd elastic scattering was made in terms of Faddeev equations as described in Ref. [10]. The NN interactions used in the calculations are CD-Bonn [28], AV18 [29], Nijmegen-I, Nijmegen-II, and Nijmegen-93 [30], which reproduce the set of NN data with a reduced χ^2 close to unity. The 2π-exchange TM-3NF [4] has been used. The TM-3NF depends on a cutoff parameter of the πNN vertex function which is adjusted to reproduce the experimental triton binding energy [31] for each NN potential separately. High total angular momenta j of the NN subsystem and the total J of the 3N system are needed to obtain converged results. Stable numbers appear for $j_{\max} = 5$ and $J_{\max} = 25/2$.

The calculations with NN forces alone significantly underestimate the cross section irrespective of the choice of NN forces in the region $\theta_{\mathrm{c.m.}} = 60°-180°$. On the other hand, the calculations adding the TM-3NF lead to an excellent agreement with the data. Note that the difference seen at forward angles is due to the neglect of Coulomb interactions in the present Faddeev calculations. It is rather remarkable to see that the predictions are independent of the input NN forces. This excellent description clearly indicates that the strengths of the NN and TM-3N forces seem to be adequate, even though the NN and 3N forces are not consistently derived within one scheme.

The vector analyzing power A_y^d data deviate from the NN force predictions largely at around 100° and to a lesser extent at 150°, while they are well described by adding the 3NF, particularly in combination with CD-Bonn.

The descriptions of the tensor analyzing powers A_{xx}, A_{yy}, and A_{xz} by the NN forces only are moderate. There are noticeable differences, for example, around 140° in A_{yy} or at 60° in both A_{xx} and A_{yy}. It is interesting to find that the inclusion of our 3NF deteriorates to a large extent the description of the data. We also note that the predictions for A_{xz} adding the 3NF show a noticeable NN input dependence.

In Fig. 2, the data of the tensor-to-vector polarization transfer coefficients $K_{xx}^{y'}$ and $K_{yy}^{y'}$ as well as the induced polarization $P^{y'}$ at $\theta_{\mathrm{c.m.}} = 120°, 130°$, and 150° are shown together with $K_{xz}^{y'}$ at 177.3°. $K_{ij}^{y'}$ and $P^{y'}$ are obtained in terms of the outgoing reactant laboratory frame [32], but they are plotted in Fig. 2 against the c.m. scattering angle.

$K_{xx}^{y'}$ data at 120° and 130° where relatively large 3NF effects are predicted are consistent with the CD-Bonn NN force only calculation. The 3NF prediction, however, shifts the calculation upwards leading to a poor agreement. On the other hand, $K_{yy}^{y'}$ data show a good agreement with the NN + 3NF calculations showing the importance of 3NF.

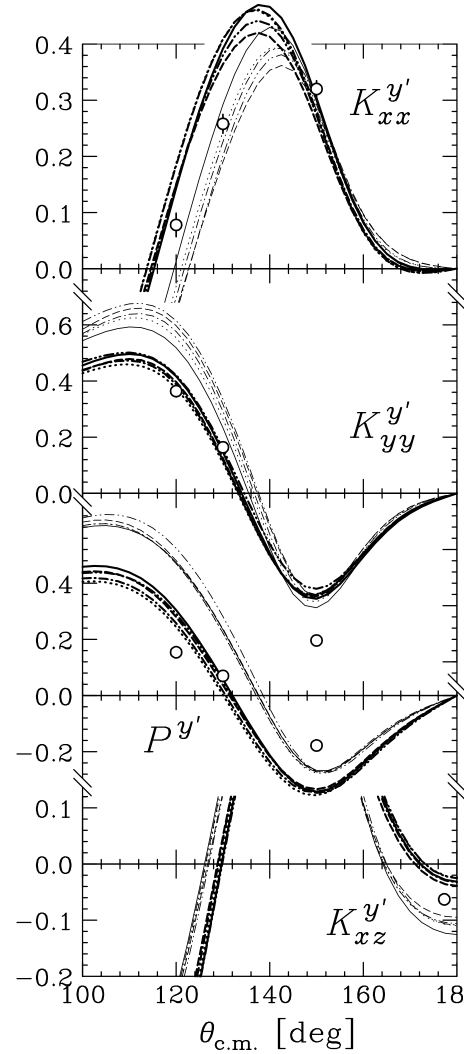

FIG. 2. Experimental tensor-to-vector polarization transfer coefficient $K_{xx}^{y'}$, $K_{yy}^{y'}$, and $K_{xz}^{y'}$ and induced polarization $P^{y'}$ for $\vec{d} + p \rightarrow \vec{p} + d$ elastic scattering at 270 MeV (open circles). Theory as in Fig. 1. Only statistical errors are indicated.

At 150° neither 3NF effects nor NN force dependence appears in the calculations. The observed $K_{xx}^{y'}$ value agrees with the predictions, while the $K_{yy}^{y'}$ value is much more negative than the predictions. This apparently shows a common defect of the data-equivalent modern NN forces, our specific 3NF, or both. At 180° owing to its special space symmetry, noncentral interactions such as spin-orbit or a tensor type do not contribute directly. The theoretical predictions with NN forces only are below the measured $K_{xz}^{y'}$ value, while the inclusion of that 3NF slightly overestimates the value. The discrepancy observed between the measured $P^{y'}$ and the Faddeev calculations (with or without 3NF) is essentially the same phenomenon recently reported [20,21] as the A_y^p puzzle at intermediate energies. Note $A_y^p = -P^{y'}$.

In summary, we have shown precise dp scattering data at $E_d = 270$ MeV: cross section, deuteron analyzing powers A_y^d, A_{xx}, A_{yy}, and A_{xz}, tensor-to-vector polarization transfers $K_{xx}^{y'}$, $K_{yy}^{y'}$, and $K_{xz}^{y'}$, and the induced polarization $P^{y'}$. The measured cross section which is underestimated by the Faddeev calculations with the recent data-equivalent NN forces in $\theta_{\text{c.m.}} = 60°-180°$ are excellently reproduced by the calculations which take into account the TM-3NF. The deuteron vector analyzing power A_y^d is also well reproduced by the calculation with the CD-Bonn NN force plus TM-3NF. These facts could be considered as the clearest signatures of 3NF effects. However, the same calculation fails to explain the tensor analyzing powers. The inclusion of the TM-3NF somewhat deteriorates the moderate agreement obtained by the NN forces only calculations. As for the tensor-to-vector polarization transfer, the significant difference between data and the NN force predictions is removed in one case and overcompensated in other ones. The induced polarization deduced from the polarization transfer measurement confirms the similar disagreement shown recently in A_y^p for $\vec{p}d$ scattering [20,21]. These results clearly indicate the necessity of 3NF effects, since NN force predictions alone do not describe the data. They also show that the 2π-exchange 3NF properly adjusted to the 3N bound state leads to effects which have overall the right sizes, though not always shifting the wrong NN force only predictions into the data. Clearly there are deficiencies in the spin dependencies of the TM-3NF. We employed that force due to practical reasons. It will be interesting to apply other theoretical 3NF models such as those proposed in Refs. [13,33]. At the same time the efforts to modify the TM-3NF [5,34,35] are also very important. They are inspired by chiral perturbation theory [7].

The present high precision data set constitutes the most substantial one for the dp elastic scattering observables at intermediate energies and therefore serves as the best testing ground for the theoretical investigation of 3NF effects.

We acknowledge the outstanding work of the RIKEN Accelerator group for delivering excellent proton and deuteron beams. This work was supported financially in part by the Grant-in-Aid for Scientific Research Numbers 04402004 and 10304018 of Ministry of Education, Science, Culture and Sports of Japan, by the Deutsche Forschungsgemeinschaft, and by the Polish Committee for Scientific Research under Grant No. 2P03B02818. The numerical calculations have been performed on the CRAY T90 and T3E of the John von Neumann Institute for Computing, Jülich, Germany.

*Electronic address: sakai@phys.s.u-tokyo.ac.jp

[1] B. M. Axilrod and E. J. Teller, J. Chem. Phys. **11**, 299 (1943).
[2] J. Carlson *et al.*, Rev. Mod. Phys. **70**, 743 (1998).
[3] M. R. Robilotta, Few-Body Syst. Suppl. **2**, 35 (1987).
[4] S. A. Coon *et al.*, Nucl. Phys. **A317**, 242 (1979).
[5] D. Hüber *et al.*, Phys. Rev. C **58**, 674 (1998).
[6] D. Hüber *et al.*, LANL Report No. nucl-th/9910034.
[7] J. L. Friar *et al.*, Phys. Rev. C **59**, 53 (1999).
[8] A. Kievsky, Phys. Rev. C **60**, 034001 (1999).
[9] S. A. Coon *et al.*, Phys. Rev. C **48**, 2559 (1993).
[10] W. Glöckle, H. Witała, D. Hüber, H. Kamada, and J. Golak, Phys. Rep. **274**, 107 (1996).
[11] A. Fonseca, Phys. Rev. Lett. **83**, 4021 (1999), and references therein.
[12] H. Witała *et al.*, Phys. Rev. C **49**, R14 (1994).
[13] J. Carlson *et al.*, Nucl. Phys. **A401**, 59 (1983); R. Schiavilla *et al.*, *ibid.* **A449**, 219 (1986).
[14] W. Tornow *et al.*, Phys. Lett. B **257**, 273 (1991).
[15] W. Tornow *et al.*, Phys. Rev. C **57**, 555 (1998).
[16] M. Viviani, Nucl. Phys. **A631**, 111c (1998).
[17] N. Sakamoto *et al.*, Phys. Lett. B **367**, 60 (1996).
[18] H. Witała *et al.*, Phys. Rev. Lett. **81**, 1183 (1998).
[19] S. Nemoto *et al.*, Phys. Rev. C **58**, 2599 (1998).
[20] E. J. Stephenson *et al.*, Phys. Rev. C **60**, 061001 (1999).
[21] R. Bieber *et al.*, Phys. Rev. Lett. **84**, 606 (2000).
[22] R. B. Wiringa *et al.*, Phys. Rev. C **29**, 1207 (1984).
[23] H. Okamura *et al.*, AIP Conf. Proc. **293**, 84 (1994).
[24] T. Ichihara *et al.*, Nucl. Phys. **A569**, 287c (1994).
[25] S. Ishida *et al.*, AIP Conf. Proc. **343**, 182 (1995).
[26] H. O. Meyer *et al.*, Phys. Rev. C **23**, 616 (1981).
[27] R. A. Arndt and L. D. Roper, *Scattering Analysis Program* (SAID), Virginia Polytechnic Institute and State University (unpublished); see also Phys. Rev. C **56**, 3005 (1997), and references therein.
[28] R. Machleidt *et al.*, Phys. Rev. C **53**, R1483 (1996).
[29] R. B. Wiringa *et al.*, Phys. Rev. C **51**, 38 (1995).
[30] V. G. Stoks *et al.*, Phys. Rev. C **49**, 2950 (1994).
[31] A. Nogga *et al.*, Phys. Lett. B **409**, 19 (1997).
[32] G. G. Ohlsen, Rep. Prog. Phys. **35**, 717 (1972).
[33] H. T. Coelho *et al.*, Phys. Rev. C **28**, 1812 (1983).
[34] S. Ishikawa, Phys. Rev. C **59**, R1247 (1999).
[35] H. Kamada *et al.*, LANL Report No. nucl-th/9904060.